Multiple observers

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- Global causal structure with multiple laboratories
- Time orientation in quantum theory
- Quantum compatibility of multiple laboratories

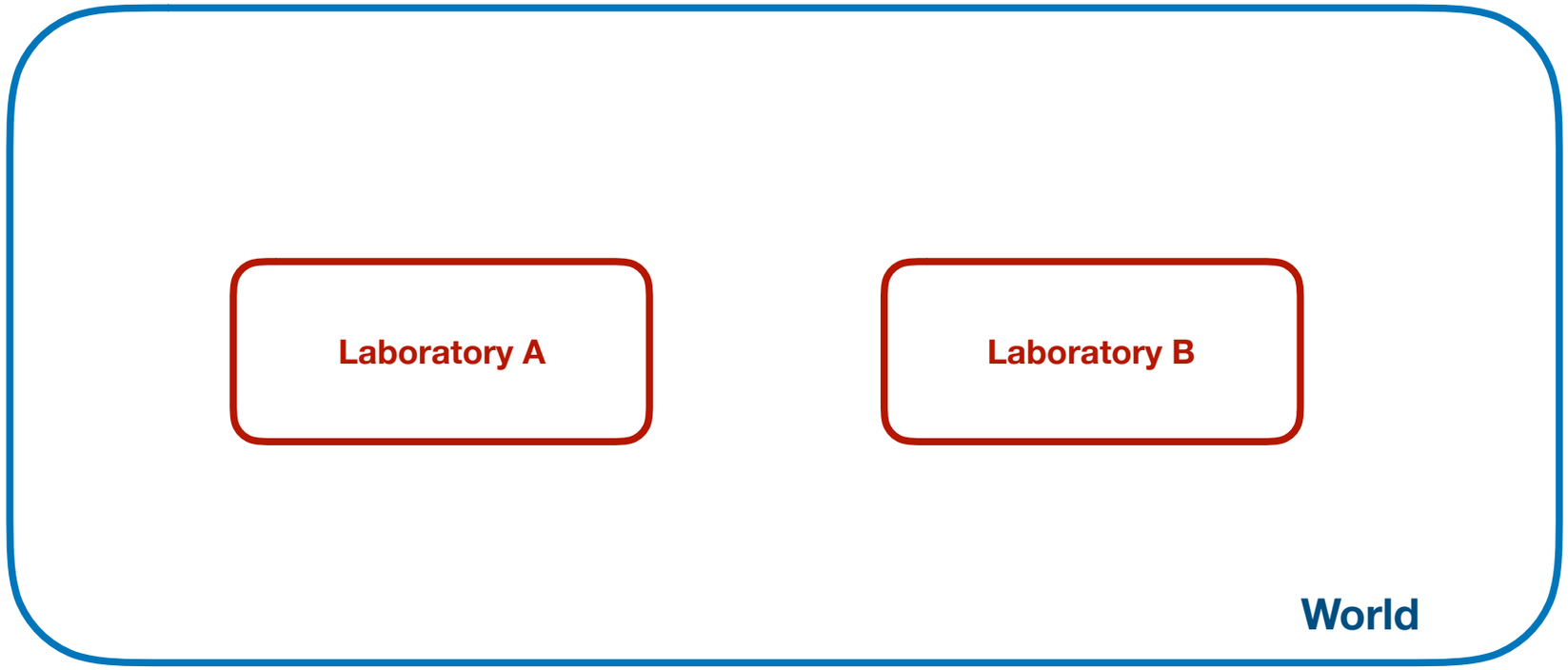
There are two ways of approaching quantum theory

1: Reality is a quantum state ψ. ("Realistic interpretation of **ψ**")
Then we need a complicated story to be given, to justify the appearance in the world of definite facts ("measurement results").
Example: Many-World interpretation.

2: Reality is given by the definite facts of the world. ("Epistemic interpretation of **ψ**")
Then we have definite 'observations', obtained by a given 'observer', or in a given 'laboratory'.
Example: Operationalism.

My sympathy is for the second, but when the observers are multiple, care is required.

What if we have several observers? Several laboratories?



Intriguing relation to general relativity: Gravity can be seen as the existence of non trivial transformations between different observers of spacetime locations.

=> Interesting question 1: what about time ordering and time orientation?
=> Interesting question 2: What about quantum compatibility of the observations?

=> Interesting question 1: Is reality invariant under time reversal?

1: Reality is a quantum state ψ: YES**.** The Schrödinger equation (and the Wheeler de Witt equation) does not have a preferred time orientation.

2: Reality is given by the definite facts of the world: apparently NO**.** A quantum measurement is time oriented.

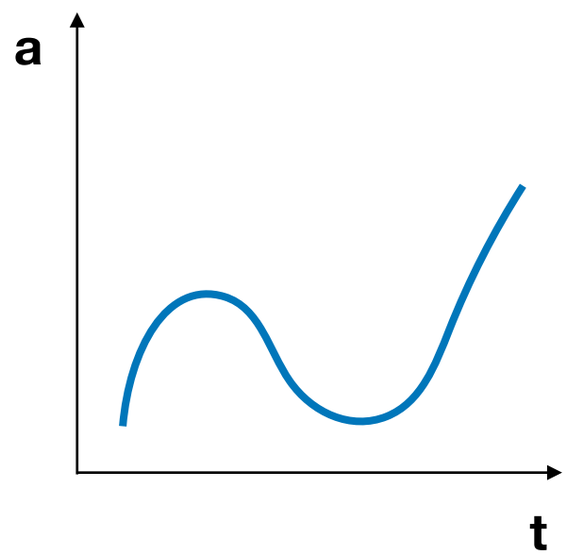
=> **Interesting question 1: Is reality invariant under time reversal?**

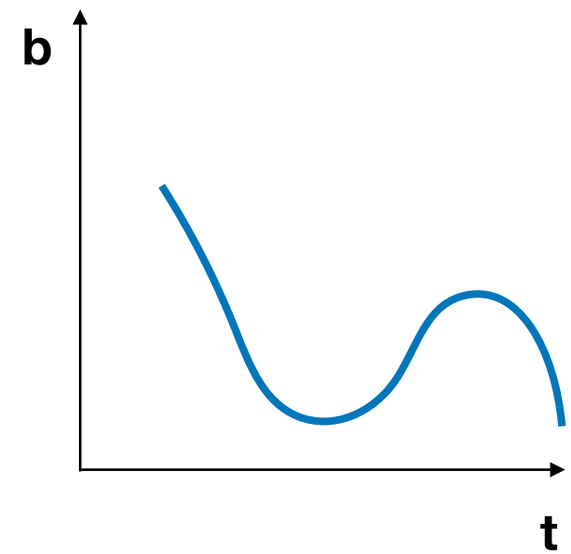
Facts about classical (non quantum) physics:

- **Mechanical phenomena <u>are not</u> time oriented**: given a classical history satisfying the equations of motion, the time (CPT) reversed trajectory also satisfies the equations of motion.)

- **Thermal phenomena <u>are</u> time oriented**: ($dS/dt \geq 0$), but **only** in the special configurations where entropy is low at one end of the of the history (called "past").
Hence time reversal invariance is not broken by thermal dynamics by itself: it is broken by the special properties of some individual histories with respect to a given definition of macroscopic variables (a given coarse graining).

=> **Only special initial conditions give rise to a preferred time orientation.**



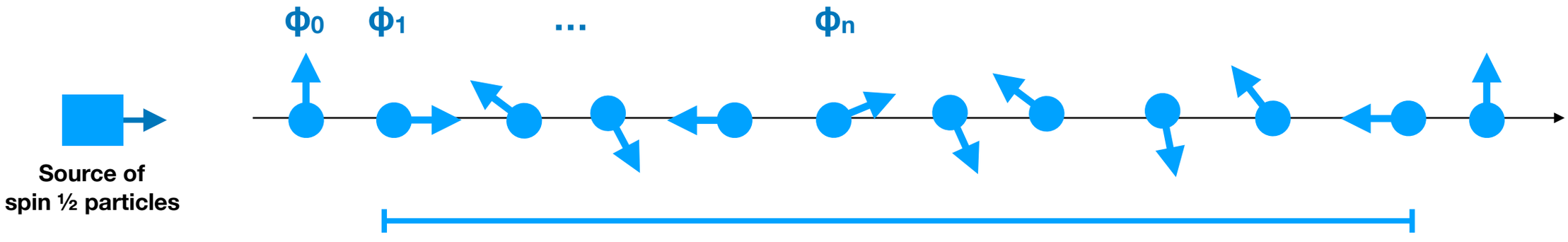


b(t) = a(T-t)

If a(t) satisfies the classical equations of motion, so does b(t)

=> What about quantum theory in the epistemic perspective?

Fact: Consider a sequence of quantum measurements.
Example: a sequence of measurement of the spin along directions ϕ_n



Results of many runs:

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+	+	+	+	-	+	-	+	-	-
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-	-	-	-	+	-	-	-	+	-
+	-	+	+	+	-	-	+	-	+
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+	-	+	+	+	-	-	+	+	+

$$
a^{(r)}_t = \begin{matrix}
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\end{matrix}
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$$b^{(r)}_t = a^{(r)}_{T-t}$$

$a^{(r)}_t =$

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$b^{(r)}_t =$

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$$a^{(r)}_t = b^{(r)}_{T-t}$$

$a^{(r)}_t =$

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$b^{(r)}_t =$

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If $a^{(r)}_t$ satisfies the probability distribution predicted by QM, so does $b^{(r)}_t$

Proof: $|\langle\phi_{n+1}|e^{-iHt}|\phi_n\rangle|^2 = |\langle\phi_n|e^{-iH(-t)}|\phi_{n+1}\rangle|^2$

Classical mechanics

$b(t) = a(T-t)$ If $a(t)$ satisfies the classical equations of motion, so does $b(t)$.

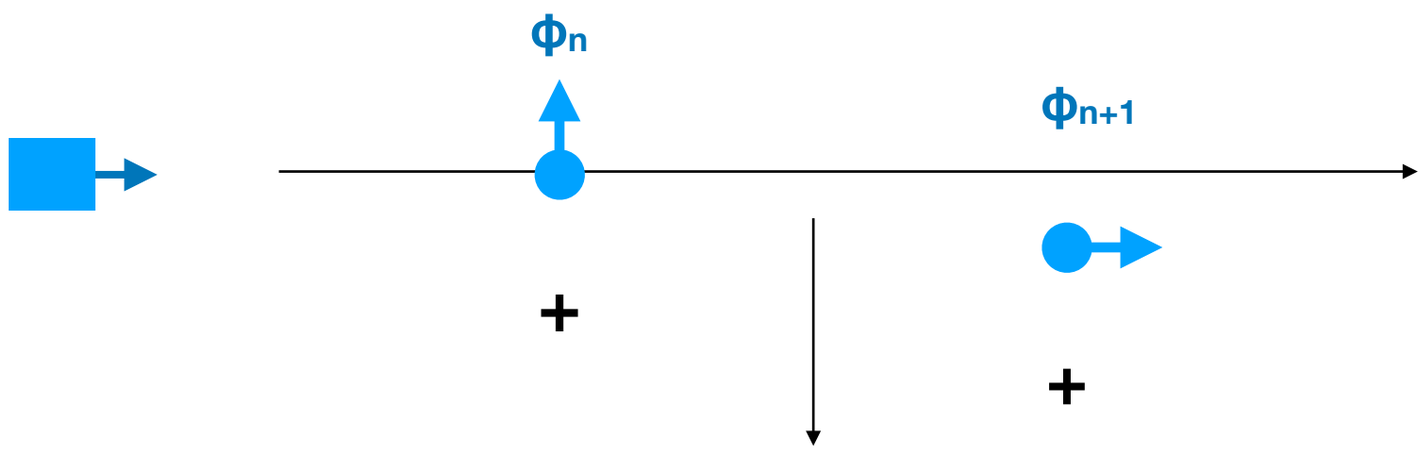
Quantum mechanics

$b^{(r)}_t = a^{(r)}_{T-t}$ If $a^{(r)}_n$ satisfies the probability distribution predicted by QM, so does $b^{(r)}_n$.

In this precise sense,
quantum theory is as time reversal invariant
as classical mechanics

Still, there is some time orientation in quantum theory. What is it?

1. We assign to a system the quantum state of the past measurement outcome, not the future one.



$$|+\rangle_{\phi_n}$$

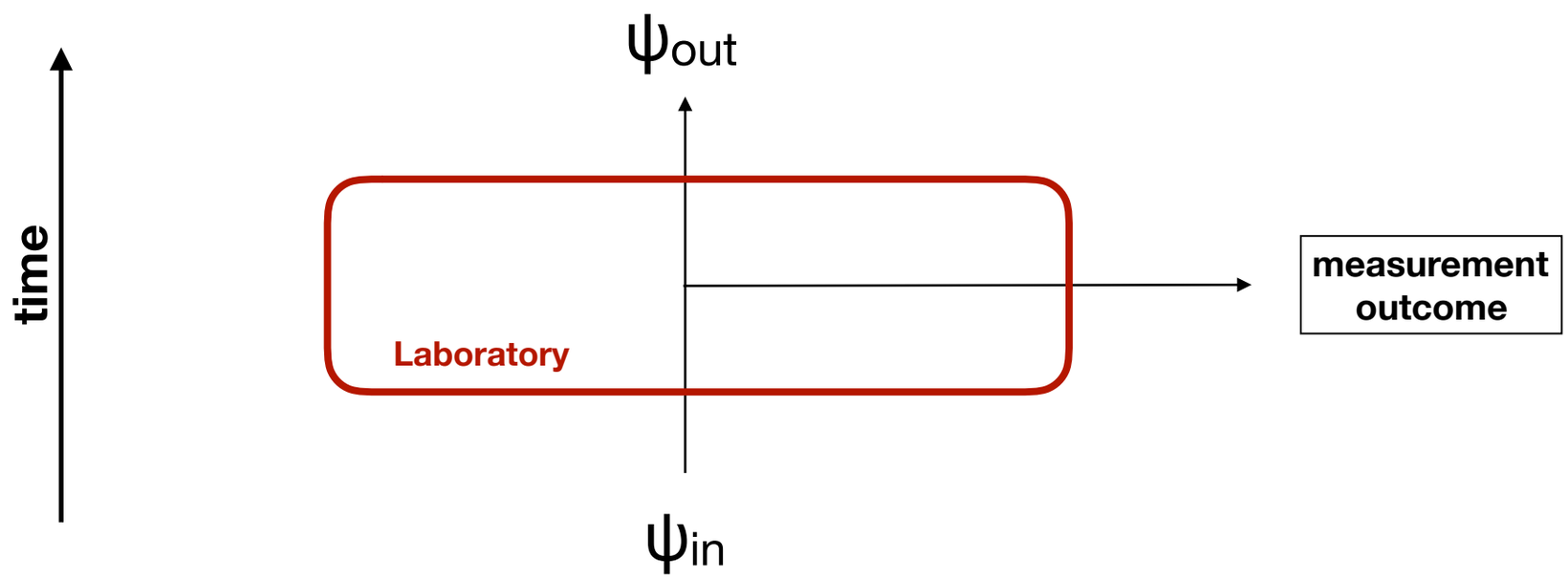
From an epistemic perspective, this is completely arbitrary!

(In fact: this is a strong argument against a realistic interpretation of ψ: a realistic interpretation of ψ adds a time orientation which is not in the facts of the world!)

CR: *An argument against the realistic interpretation of the wave function*, Foundations of Physics, 46, (2016), 1229, arXiv:1508.05533.

Still, there is some time orientation in quantum theory. What is it?

2. The observers (the laboratory) are macroscopic, information gathering, thermodynamically oriented chunks of nature.
It is this fact that introduces a time orientation.



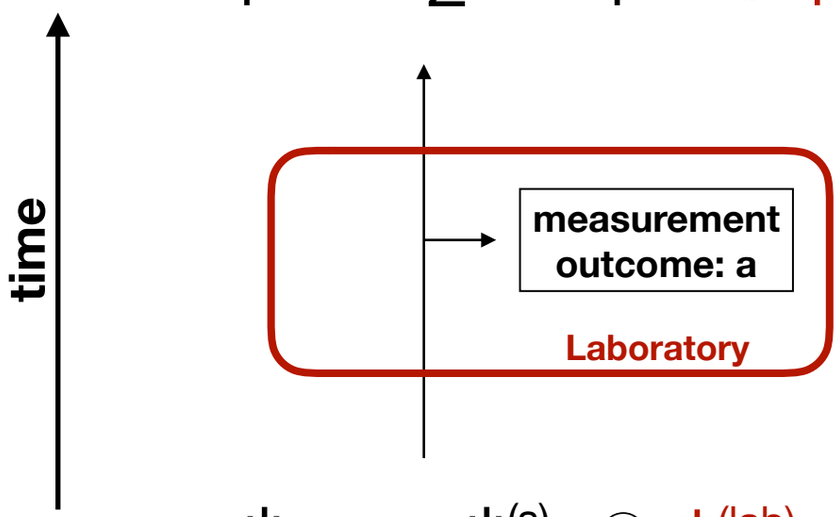
This process has a time orientation. Why?
The observers (the laboratory) are macroscopic, information gathering, thermodynamically oriented chunks of nature.
It is this fact that introduces a time orientation.
How to formalise and understand this?

For this, let us revert to a realistic interpretation of **ψ** for a moment

$\psi_{final} = \sum_a c_a \, \psi^{(s)}_a \otimes \psi^{(lab)}_a$

Generic state

$$\rho = \sum_{aa'} c_a \bar{c}_{a'} |\psi^{(s)}_a\rangle\langle\psi^{(s)}_{a'}| \qquad S = Tr[\rho \log \rho] \geq 0$$



$\psi_{initial} = \psi^{(s)}_{in} \otimes \psi^{(lab)}_{in}$

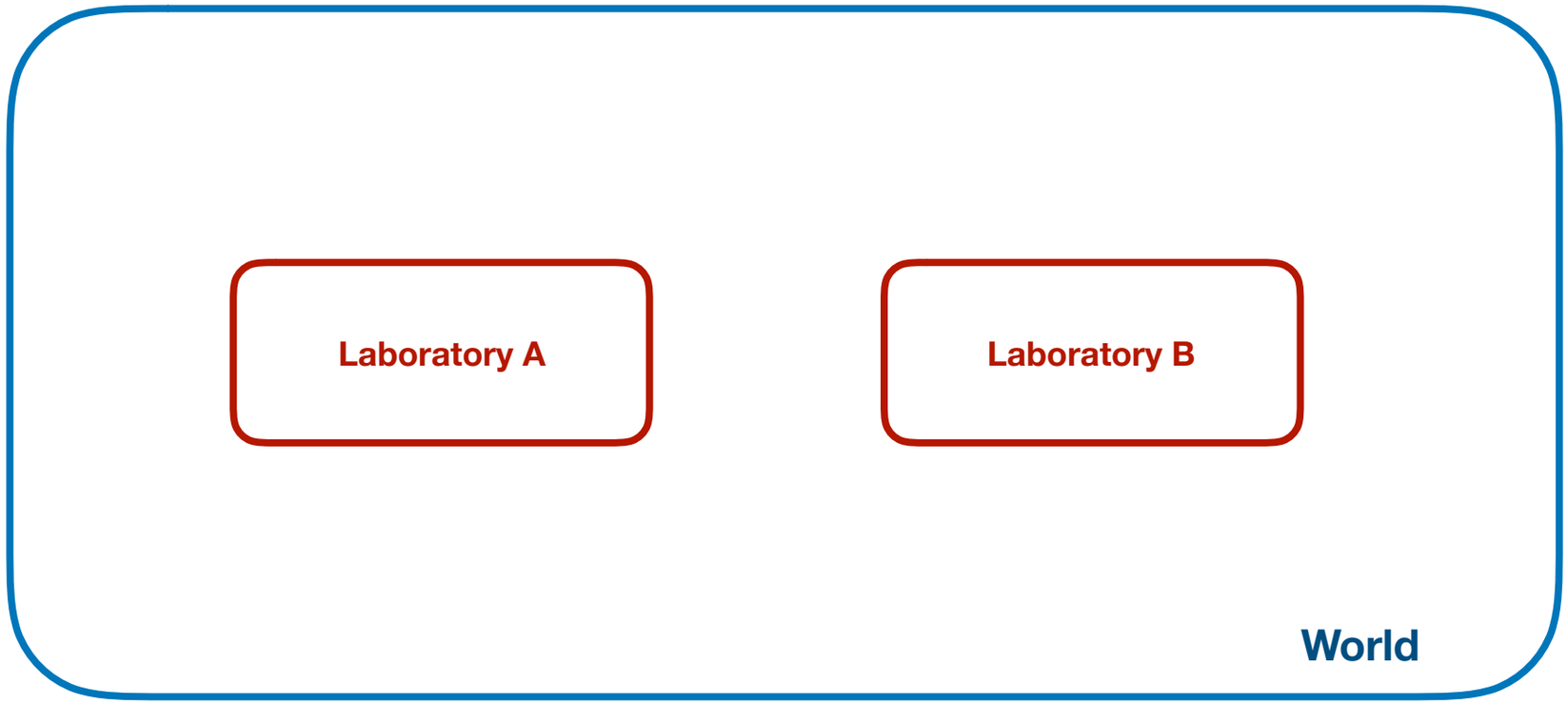
Special state !

$$\rho = |\psi^{(s)}_{in}\rangle\langle\psi^{(s)}_{in}| \qquad S = Tr[\rho \log \rho] = 0$$

Time reversal invariance is broken by the assumption that the initial state is a tensor state, hence in this sense a very special "low entropy" state.

All non-time-reversal invariant properties assumed in the epistemic framework are equivalent (and can be derived from) the assumption of an initial tensorial state. Hence they are essentially initial-low-entropy assumptions.

=> Interesting question 2: what if we have several observers? Several laboratories?



Intriguing relation to general relativity: Gravity can be seen as the existence of non trivial transformations between different observers of spacetime locations.

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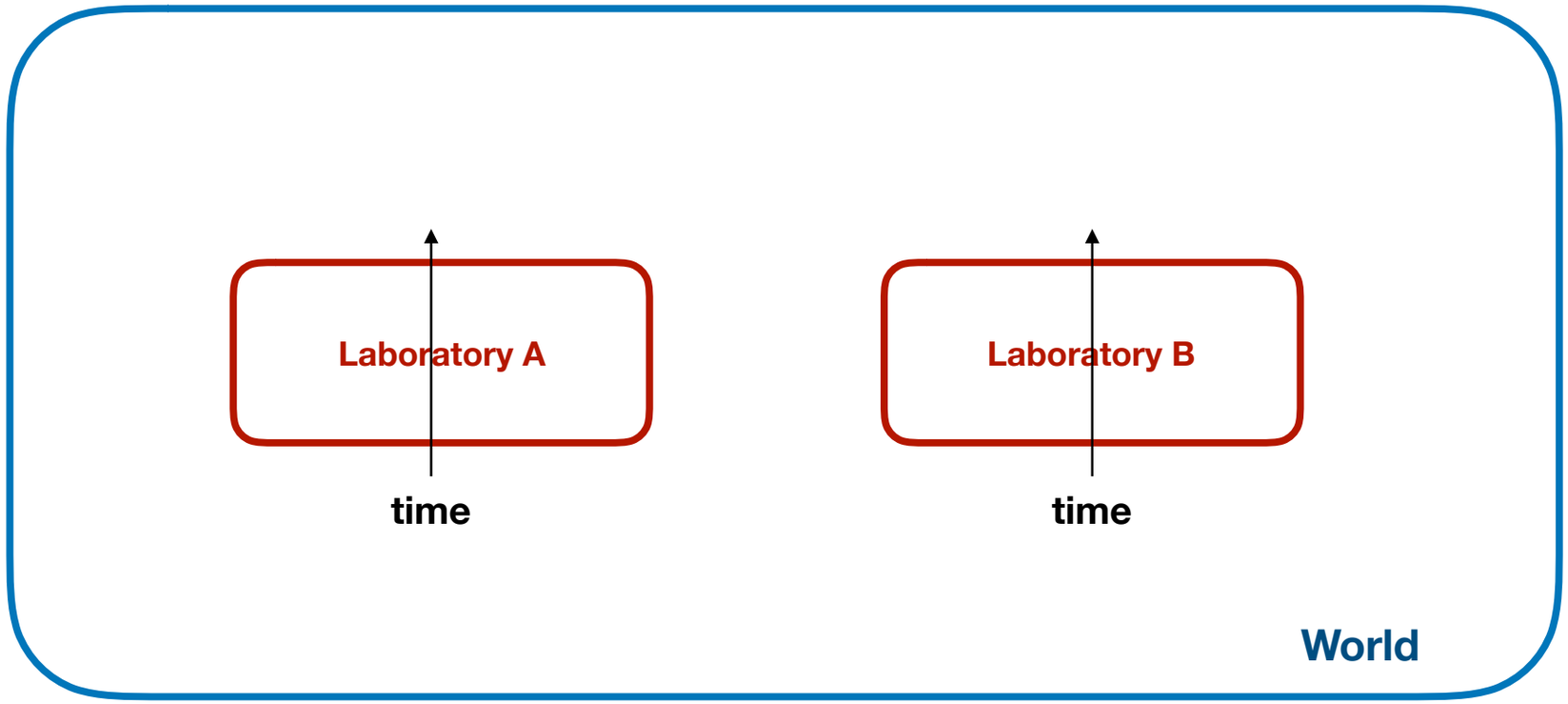

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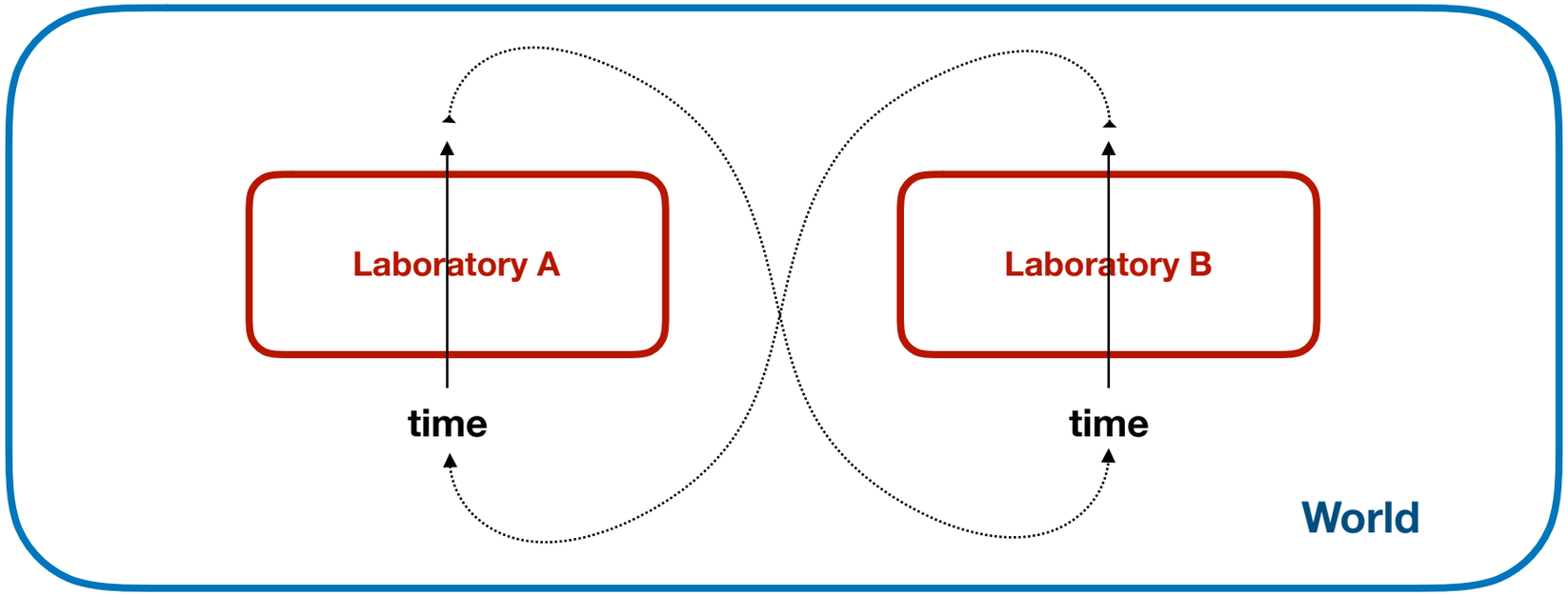

Can we have a non trivial time ordering of these time arrows?

Only if the initial input+lab states of all laboratories are all tensorial.

$$\Psi = \psi_{in}^{(\mathrm{labA})} \otimes \psi_{in}^{(\mathrm{sA})} \otimes \psi_{in}^{(\mathrm{labB})} \otimes \psi_{in}^{(\mathrm{sB})} \otimes \Psi_{out}$$

This gives the conditions on the correlations between the output and the input.

This, I think, is the full condition on “non trivial causal structures””.

The gradient of the entropy is a gradient, therefore its line integral along any closed curve is zero, therefore there can be no closed causal curves of oriented time.

This is general: closed timelike curves do not violate any known physical low, but time cannot be oriented along them, precisely because orientations given only by a (possibly generalised) entropy gradient.

CR: *Can we travel to the past? Irreversible physics along closed timelike curves*, arXiv:1912.04702.

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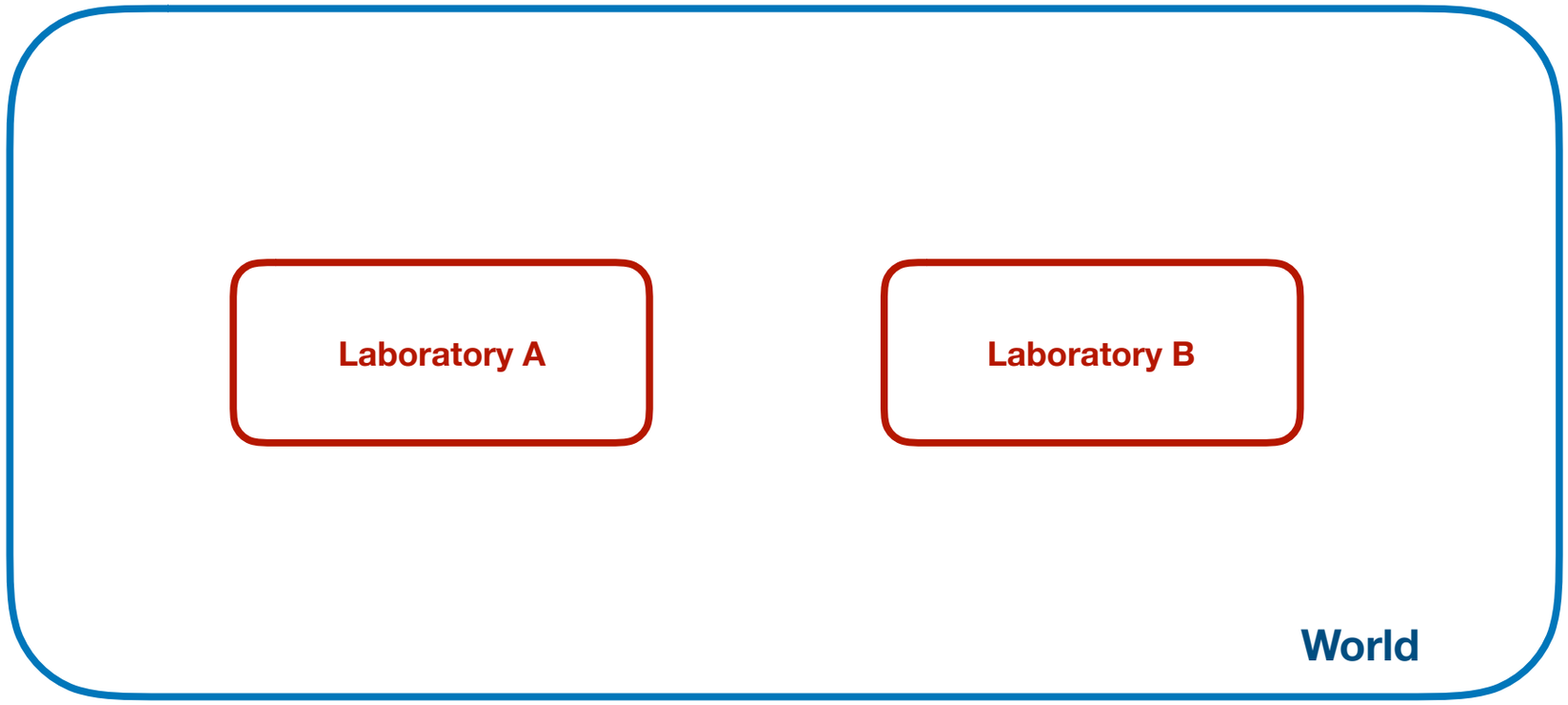

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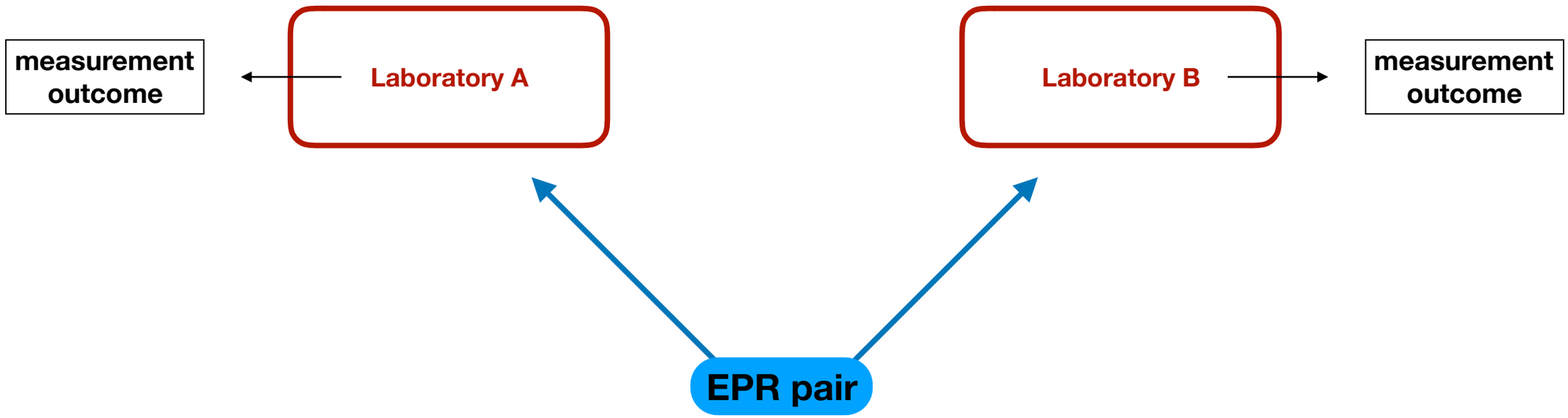


There are EPR correlations

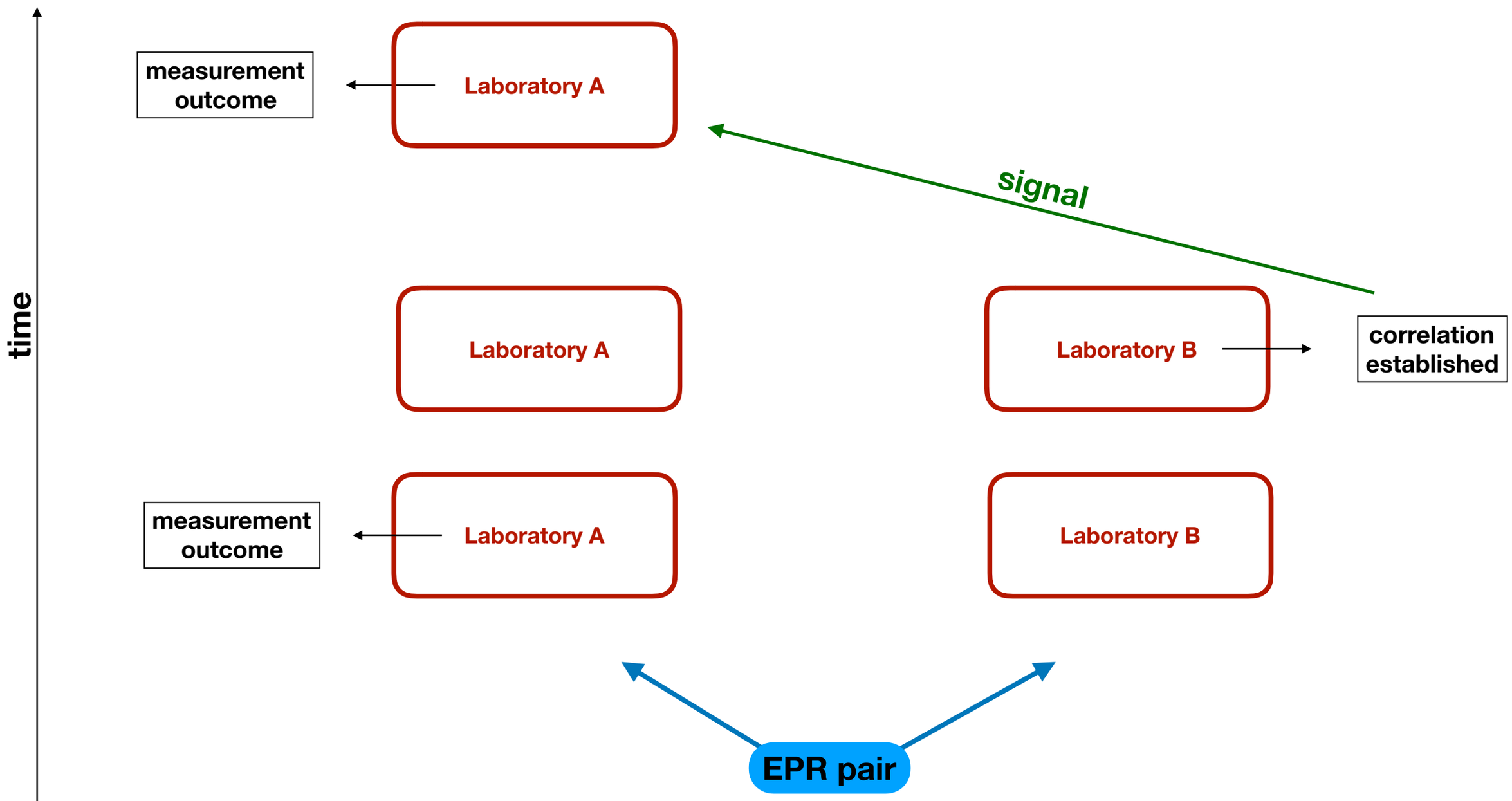
Can they be ascribed to correlated hidden variables? No, because of Bell theorem.

Can they be ascribed to instantaneous transmission? No, because of the relativistic structure of spacetime.

Puzzle

Solution

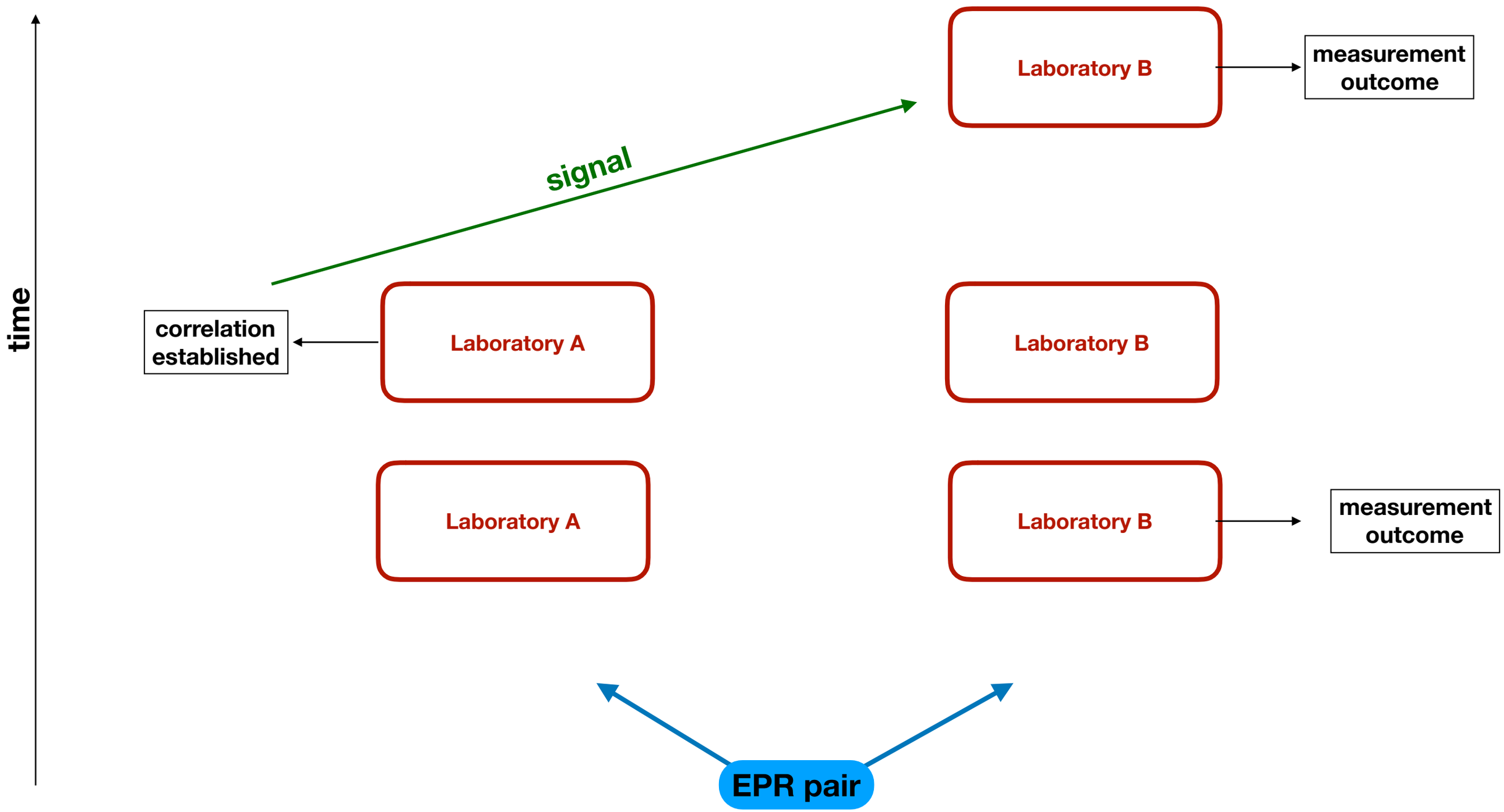
Do not take a God's eye view: look at this from the perspective of a given single observer, say A:



Pierre Martin-Dussaud, Federico Zalamea, CR. ``The notion of locality in relational quantum mechanics", Foundations of Physics, 49 (2019) 96. arXiv:1806.08150.

Solution

Do not take a God's eye view: look at this from the perspective of a given single observer, say B:



Moral: measurements outcomes are relative to a lab (observer, physical system).
They cannot be juxtaposed except when the histories they define decohere
(See: Decoherent histories: Hartle, Gell Mann)

We cannot ascribe probabilities to outcomes of operations performed
in arbitrary different spacetime regions,
without (heavy) hidden assumptions on their decoherence (on the boundary state).

Relevance for General Relativity:
Local quantum observes are (generically) quantum systems with respect to one another.
They cannot be assumed to define common Bell-beables.

CR: *Relational Quantum Mechanics*, International Journal of Theoretical Physics, 35, 1637 (1996). quant-ph/9609002

CONCLUSIONS

1. Quantum mechanics is time reversal invariant.

   Time reversal invariance in broken only by special initial conditions.

2. A measurement is a special interaction with peculiar initial condition (tensorial state): hence it determines a preferred time direction. This is a “low initial entropy” condition.

   Growing entropy cannot loop. Hence there can be closed timelike curves, but not closed curves with consistent time orientation.

3. Multiple observers can be quantum mechanical (“in superposition”) with respect to one another.

   Assuming that different “laboratories” yields consistent measurement outcomes requires that the corresponding histories decohere: which is not true for general boundary states.

- CR: *Can we travel to the past? Irreversible physics along closed timelike curves*, arXiv:1912.04702.
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